Special Topics on Basic EECS I
VLSI Devices
Lecture 15

Sung-Min Hong (smhong@gist.ac.kr)
Semiconductor Device Simulation Laboratory
School of Electrical Engineering and Computer Science
Gwangju Institute of Science and Technology

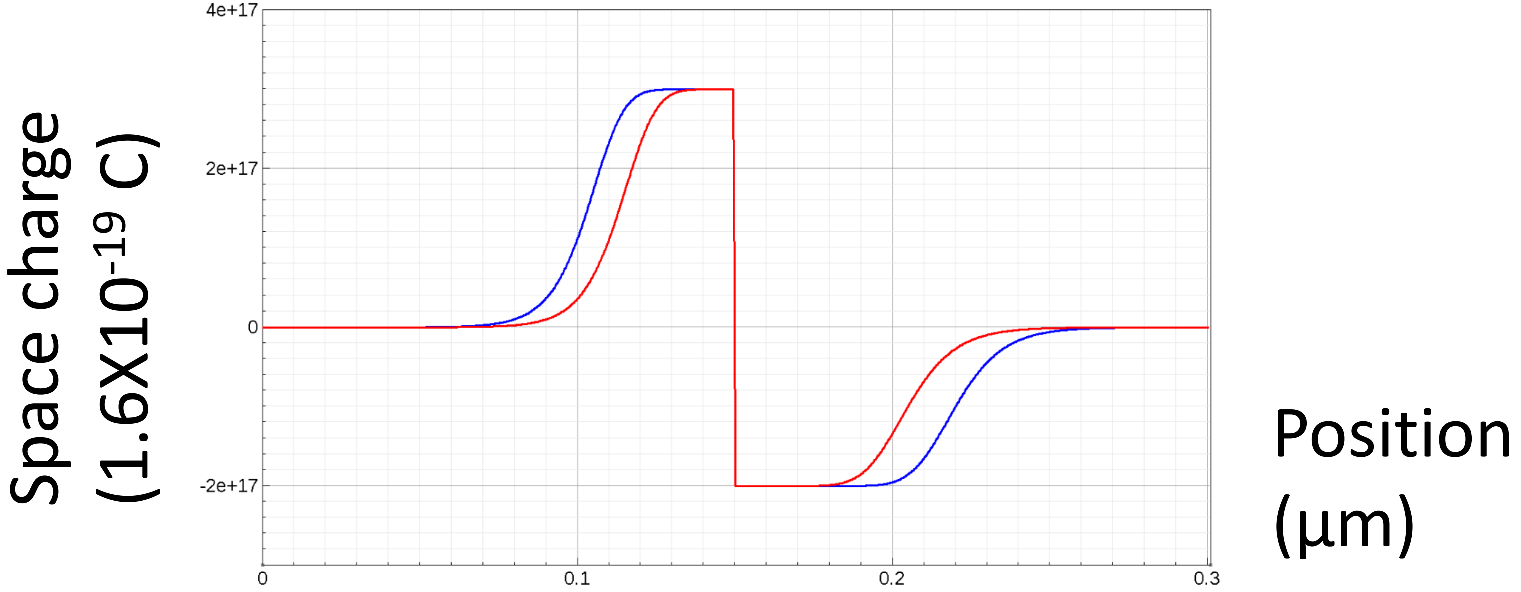
Estimation

- Distance between two curves: ~ 10 nm (n-type) & ~ 15 nm (p-type)
  - Then, for 0.5 V difference,

$$\Delta Q = q \times 4.8 \times 10^{-8}\ \mathrm{cm}^{-2}$$

  - The capacitance becomes

$$C_d = 9.6 \times 10^{-8}\ \mathrm{F\ cm}^{-2}$$



Bias dependence

- Recall that the depletion width depends on the bias.
  - With the value at equilibrium

$$W_d = W_{d0}\sqrt{1-\frac{V_{app}}{\phi_{bi}}}$$

  - The capacitance becomes

$$C_d = C_{d0}\frac{1}{\sqrt{1-\frac{V_{app}}{\phi_{bi}}}}$$

Equations in a 1D structure

- Recall the following equations:
  - Current densities

$$J_n(x) = -q\mu_n(x)n(x)\frac{d}{dx}\phi_n(x) \qquad \text{Taur, Eq. (2.98)}$$

$$J_p(x) = -q\mu_p(x)p(x)\frac{d}{dx}\phi_p(x) \qquad \text{Taur, Eq. (2.99)}$$

  - At the i-th contacts,

$$\phi_n = \phi_p = V_i$$

Quasi-Fermi potential

- For example, consider $\phi_p(x)$.
  - Everywhere,

$$\frac{d}{dx}\phi_p(x) = -\frac{J_p(x)}{q\mu_p(x)p(x)}$$

Taur, Eq. (2.104)

  - In the quasineutral p-region, $p(x) = p_{p0}(x) + \Delta p_p(x)$,

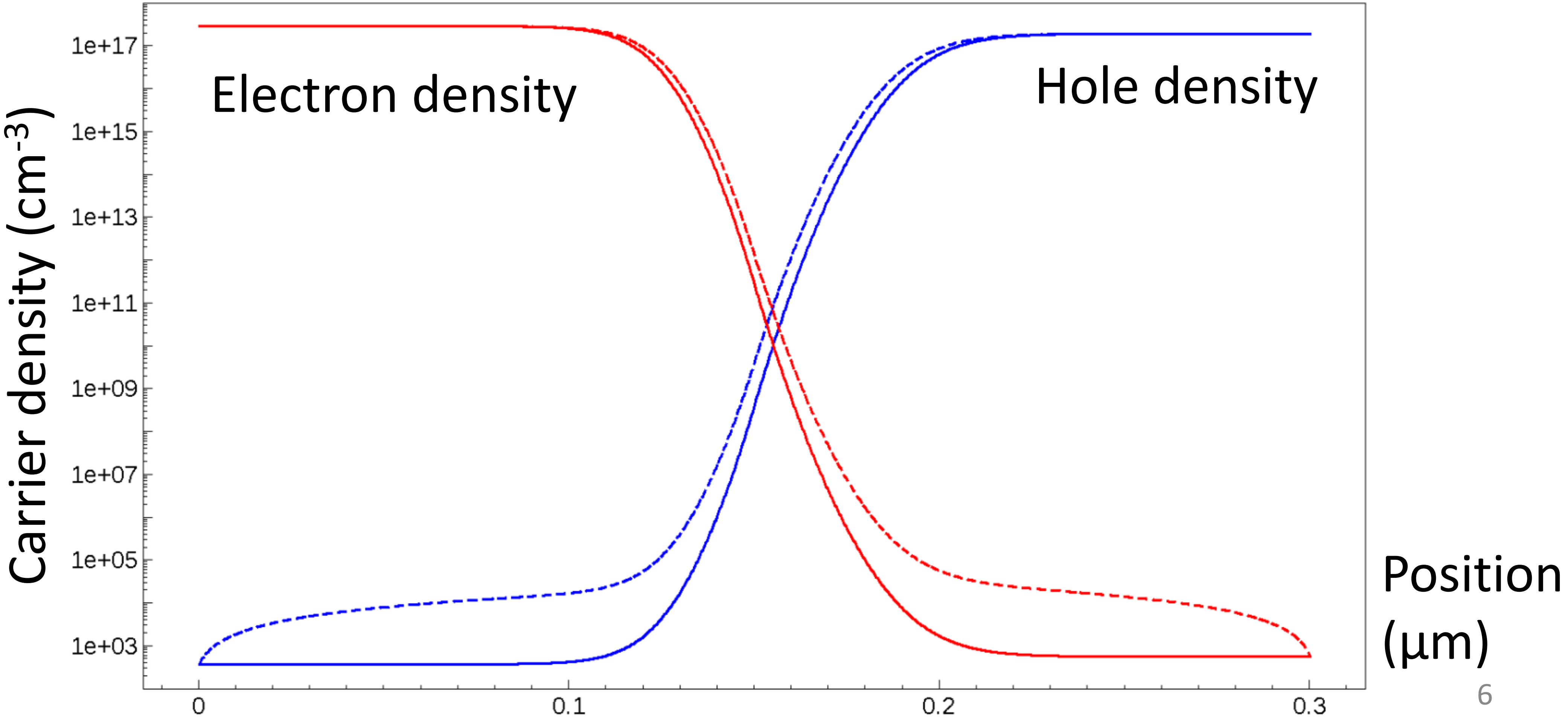
$$\frac{d}{dx}\phi_p(x) \approx -\frac{J_p(x)}{q\mu_p(x)p_{p0}(x)}$$

Small at low injection

High density

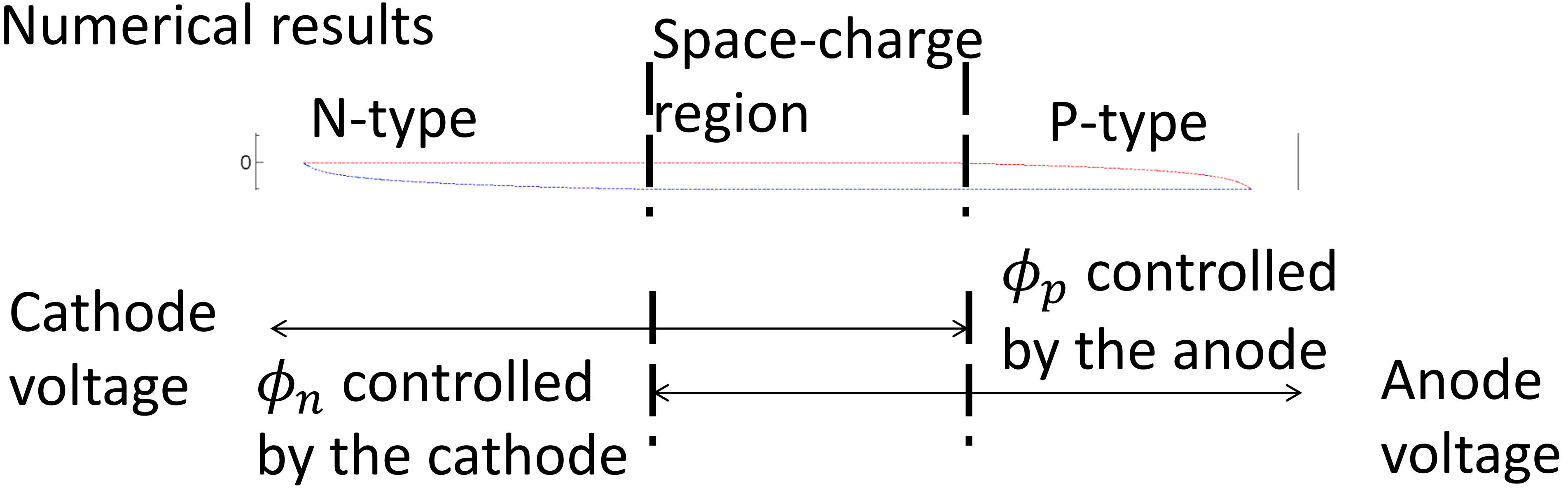
Across the space-charge region

- What is $\frac{d}{dx}\phi_p(x)$? (Solid: 0 V, dash: 0.1 V)



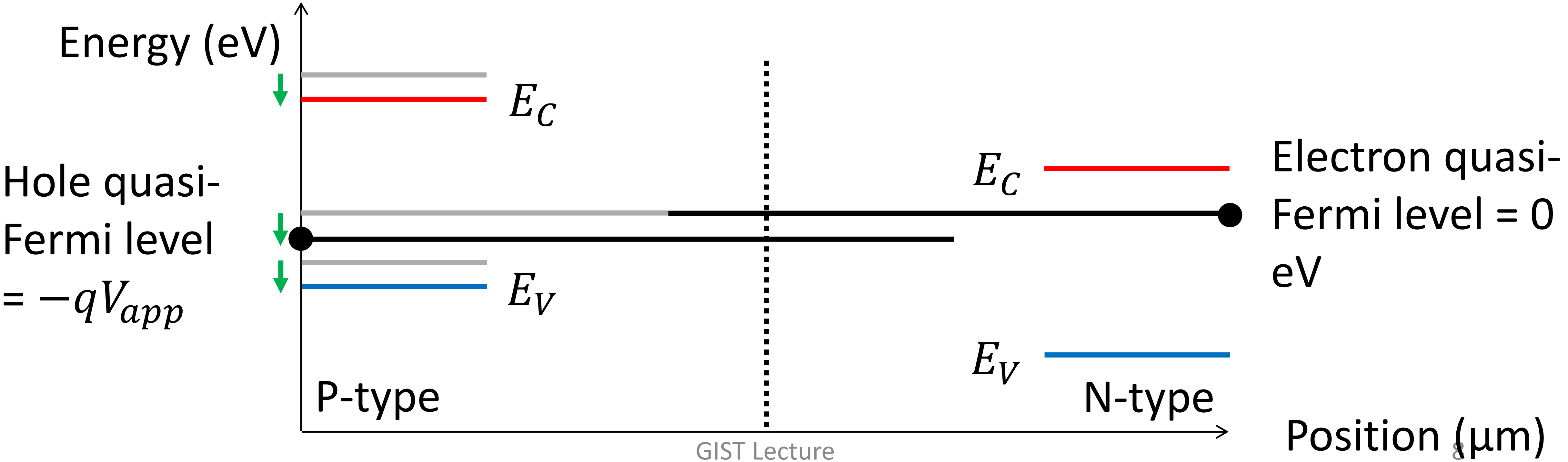
Simply speaking,

- In the forward-biased diode, ϕ_p and ϕ_p are essentially constant across the space-charge region.
  - ϕ_p and ϕ_p are also relatively constant across the space-charge region for the case of small reverse bias.
  - Numerical results



Energy band diagram, revisited

- Separation of quasi-Fermi levels
  - Then, what will happen to the minority carrier density?



Minority carrier densities

- We know that the potential difference across the space-charge region is $\phi_{bi} - V_{app}$.
  - However, the quasi-Fermi potential is constant.
  - For holes,

$$p_p(-x_p) = n_i \exp\left(-\frac{\phi(-x_p) - V_{anode}}{k_B T/q}\right)$$

  - Now, the potential becomes $\phi(-x_p) + \phi_{bi} - V_{app}$ at x_n. Still, $\phi_p(x_n) = V_{anode}$.

$$p_n(x_n) = p_p(-x_p) \exp\left(-\frac{\phi_{bi} - V_{app}}{k_B T/q}\right) = p_{n0}(x_n) \exp\left(\frac{V_{app}}{k_B T/q}\right)$$

Taur, Eq. (2.108)

Shockley diode equations (Law of junction)

- A similar expression holds for electrons.
  - For electrons,

$$n_p(-x_p) = n_n(x_n)\exp\left(-\frac{\phi_{bi} - V_{app}}{k_B T/q}\right) = n_{p0}(-x_p)\exp\left(\frac{V_{app}}{k_B T/q}\right)$$

Taur, Eq. (2.107)

  - For holes,

$$p_n(x_n) = p_p(-x_p)\exp\left(-\frac{\phi_{bi} - V_{app}}{k_B T/q}\right) = p_{n0}(x_n)\exp\left(\frac{V_{app}}{k_B T/q}\right)$$

Taur, Eq. (2.108)

  - For a forward(/reverse)-biased diode, we have an excess(/a depletion) of minority carriers at the boundaries of the quasineutral regions.

Band diagram, again

- A similar expression holds for electrons.
  - For electrons,

$$n_p(-x_p) = n_n(x_n)\exp\left(-\frac{\phi_{bi} - V_{app}}{k_B T/q}\right) = n_{p0}(-x_p)\exp\left(\frac{V_{app}}{k_B T/q}\right)$$

Taur, Eq. (2.107)

  - For holes,

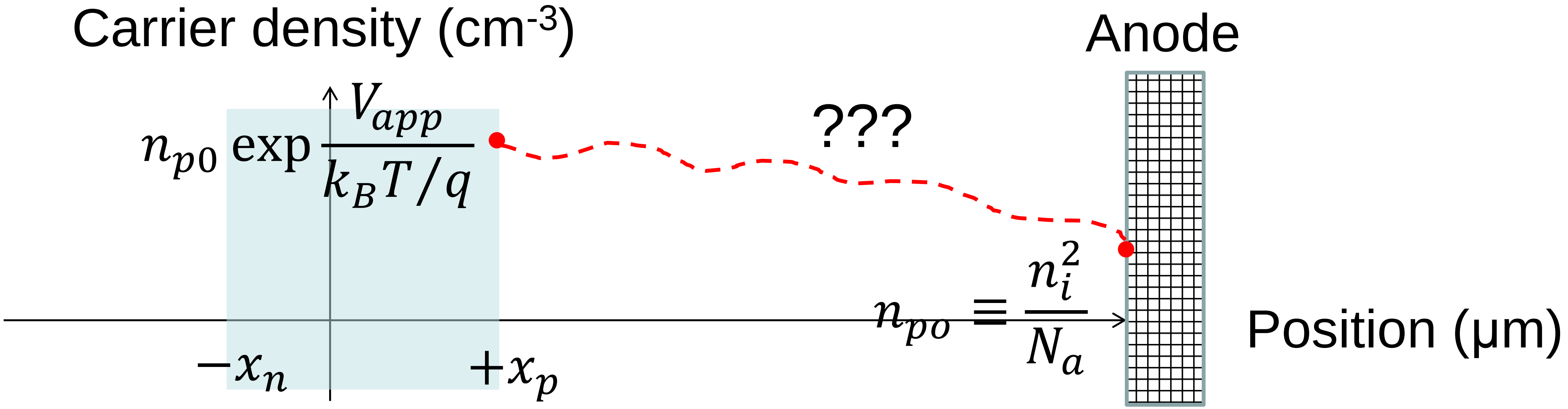
$$p_n(x_n) = p_p(-x_p)\exp\left(-\frac{\phi_{bi} - V_{app}}{k_B T/q}\right) = p_{n0}(x_n)\exp\left(\frac{V_{app}}{k_B T/q}\right)$$

Taur, Eq. (2.108)

  - For a forward(/reverse)-biased diode, we have an excess(/a depletion) of minority carriers at the boundaries of the quasineutral regions.

Problem simplified

- With the law of junction, we have a simplified problem.
  - Boundary densities are fixed.
  - Electron density profile in the p-type region?



Electron continuity in p-type

- We must solve the electron continuity equation.

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial}{\partial x}J_n - R_n + G_n$$

Taur, Eq. (2.109)

  - In the p-type region, the electric field is weak.

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2}{\partial x^2}n - \frac{n - n_{p0}}{\tau_n}$$

Taur, Eq. (2.113)

  - At steady state,

$$\frac{d^2}{dx^2}n = \frac{n - n_{p0}}{D_n \tau_n} = \frac{n - n_{p0}}{L_n^2}$$

Taur, Eq. (2.115)

Electron diffusion length

Solution of diffusion equation

- Boundary values

$$n(x_p) = n_{p0} \exp \frac{V_{app}}{k_B T/q}$$

$$n(\infty) = n_{p0}$$

  - The solution is obtained as

$$n(x) = n_{p0} \left(\exp \frac{V_{app}}{V_T} - 1 \right) \exp \left(-\frac{x - x_p}{L_n} \right) + n_{p0}$$

(Our textbook considers a finite thickness of the quasineutral region.)

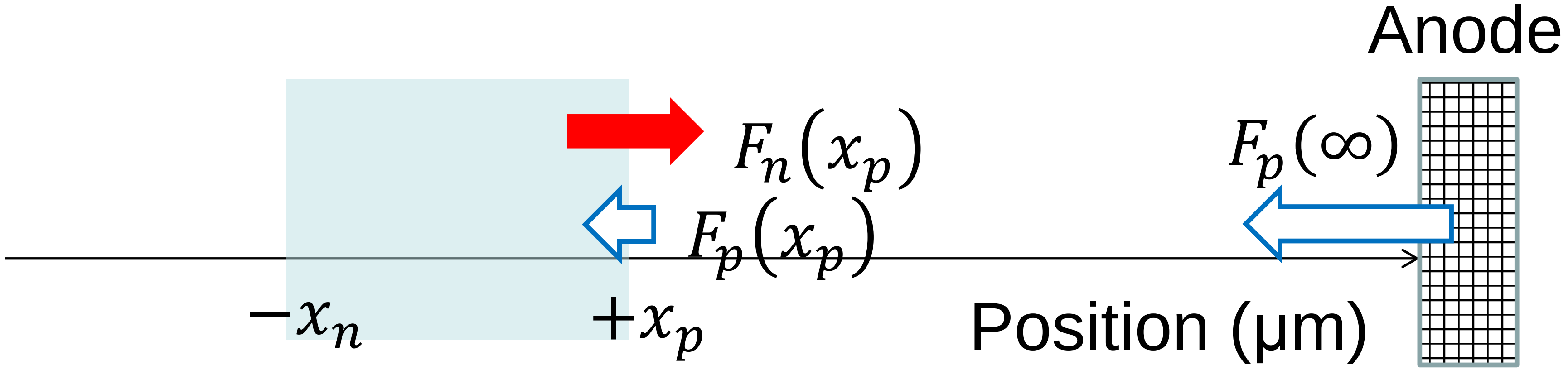
Electron flux

- The electron flux, $F_n(x)$, is found as

$$F_n(x) = -D_n \frac{dn}{dx} = \frac{D_n}{L_n} n_{p0} \left(\exp \frac{V_{app}}{k_B T/q} - 1 \right) \exp \left(-\frac{x - x_p}{L_n} \right)$$

  - $F_n(x)$ is non-uniform. The electron flux decreases as x increases.
  - $F_n(\infty)$ vanishes. All injected electrons are recombined.

$$F_p(\infty) = F_n(x_p) + F_p(x_p)$$



Thank you!